Application of Control Principles to Co-Design

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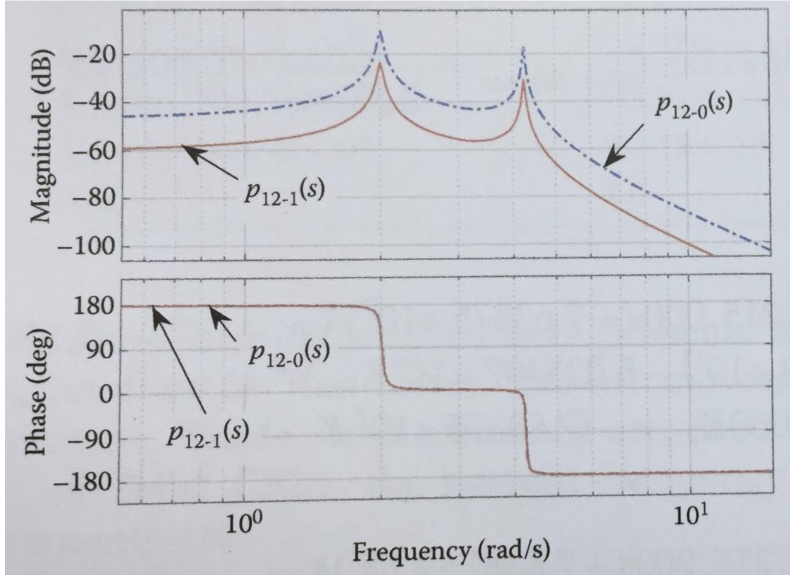
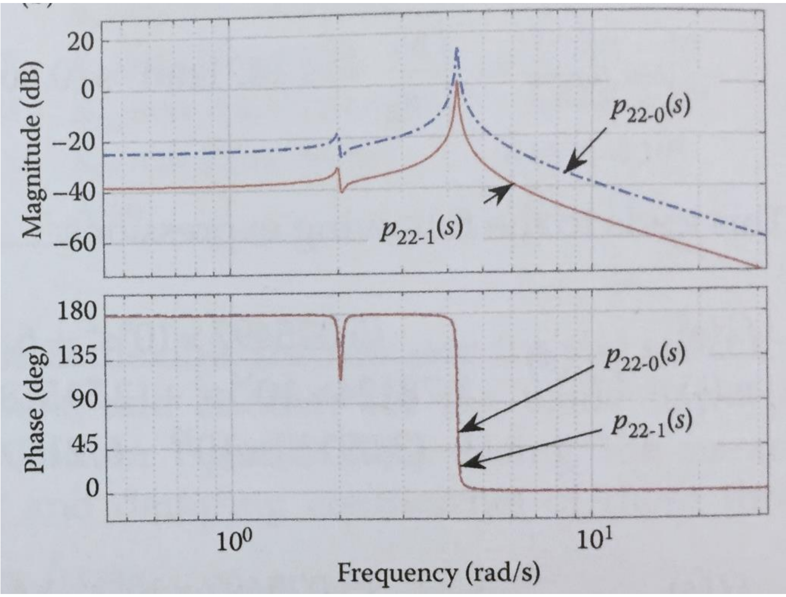
Exploiting vibrational characteristics in control co-design

- Resonance frequencies: Operating frequencies where oscillation amplitudes sharply increase
  - Locations based on geometry, mass distribution, dynamic interconnections
  - Points of high cyclic stresses
  - Sharpness of peak and slope of phase plot provide estimate of the amount of damping
- In certain cases operating under resonance conditions must be avoided
  - e.g. wind turbine
  - Drive engineering design to appropriately place the resonance points, or
  - Design controllers to reduce bandwidth
- In other applications, resonant oscillation can be utilized to harvest energy
  - e.g. Resonant wave energy harvesting





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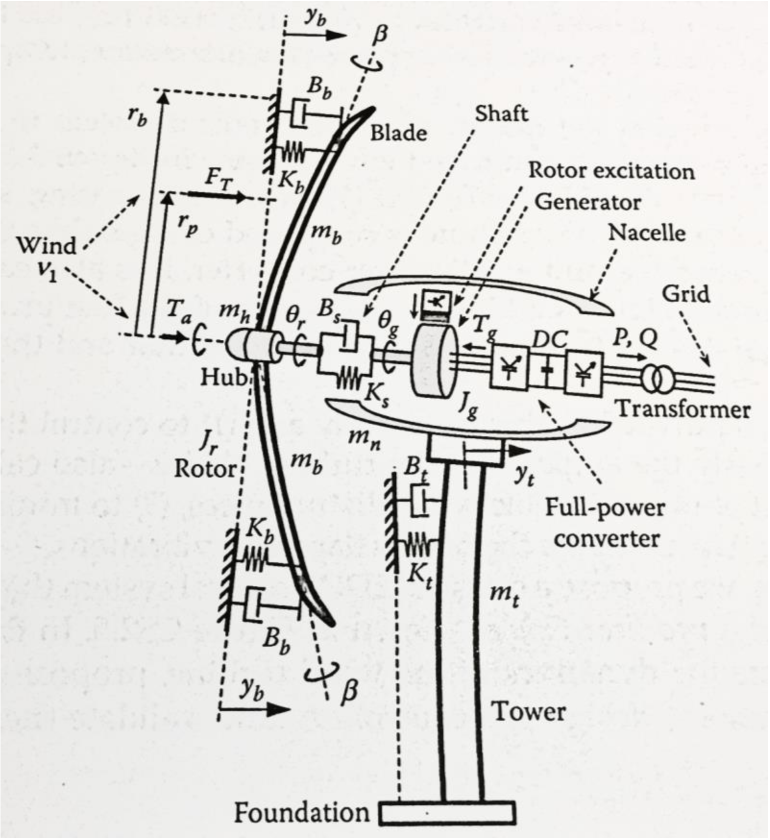
* M. Garcia-Sanz, “Robust Control Engineering,” CRC Press, 2017

Exploiting vibrational characteristics (Wind Turbines, Wave Energy)

- Under high wind speeds, blade pitch control is essential for capping the power output and for protecting mechanical components
  - Such high wind speeds could excite excessive vibrations in the structure (hence a need to prevent resonance)
  - Isolated blade pitch controllers may overlook this issue
  - Lumped parameter 3DOF vibration models, capture potential resonance situations enabling more practical control design*
  - The exercise shows how dynamic vibration absorption or mechanical design iterations (i.e. control co-design) could improve overall system characteristics.
- In wave energy converters, resonance conditions are desired to maximize energy harvesting**
  - The concept is utilized in resonant driven buoys whose natural frequency is tuned to match that of the waves.



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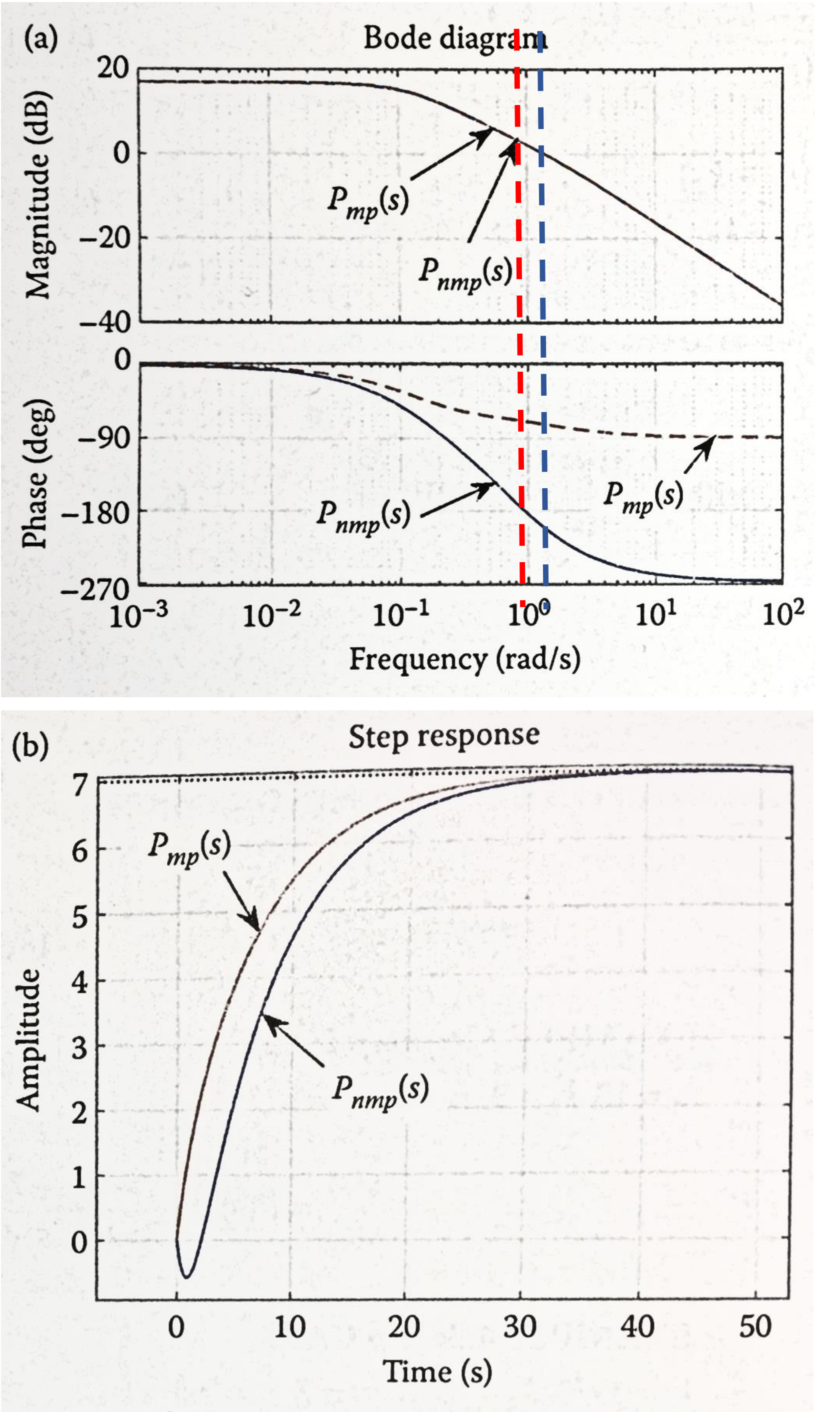
* M. Garcia-Sanz, "Robust Control Engineering," CRC Press, 2017

** D. A. Gemme, H. R. Greene II, T. A. Tucker, R. B. Sepe Jr., S. P. Bastien, "Hybrid Resonant Wave Energy Harvesting Buoy for Sensor Applications," 2013 OCEANS, San Diego

Nonminimum-Phase (NMP) Zero*, **

- An NMP zero poses constraints on robust stability
  - NMP zeros have positive real parts
  - An NMP zero reduces robustness by reducing Gain and Phase margins (GM and PM) (bandwidth limitations)
  - Characterized by an initial inverse response to step input
- Pole NMP-zero cancellation introduces or retains internal instability
- To address constraints due to NMP zeros:
  - Use control strategies, e.g. change input/output variable(s), use of feedforward action
  - Adopt co-design approach: Revisit system design and change sensing/actuation configurations or change dynamic characteristics



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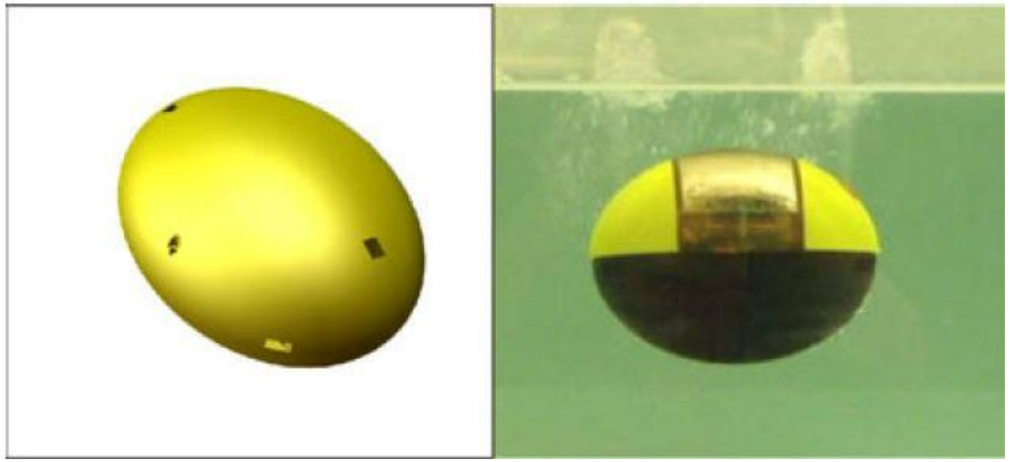
* M. Garcia-Sanz, "Robust Control Engineering," CRC Press, 2017

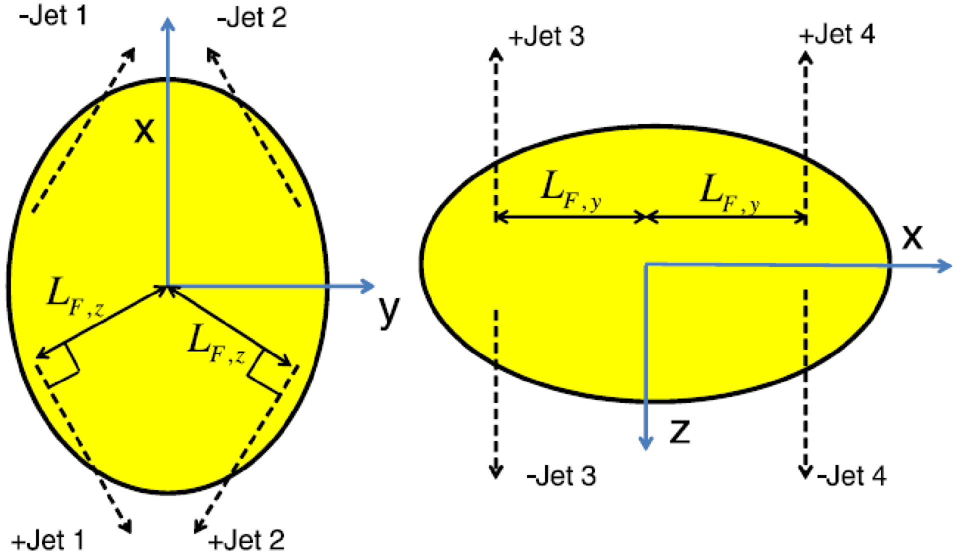
** J. B. Hoagg, D. S. Bernstein, "Nonminimum-Phase Zeros," IEEE Control Systems Magazine, June 2007

Control-Configured Underwater Vehicle*

- A spheroidal underwater surveillance/ inspection robot with no appendages or fins for locomotion
  - Ability to turn in place, conduct precise inspection
  - Agile and causing minimum water perturbation
  - Minimum interference or collision during task



- The shape has inherent instabilities (e.g. Munk moment) but is well-suited for tasks
- Fixed-angle jets were designed for control
  - Jets were designed to prevent NMP characteristics and uncontrollable modes
  - Inward angled jets led to unstable but easily stabilizable dynamics
  - Actuations designed to aid controllability



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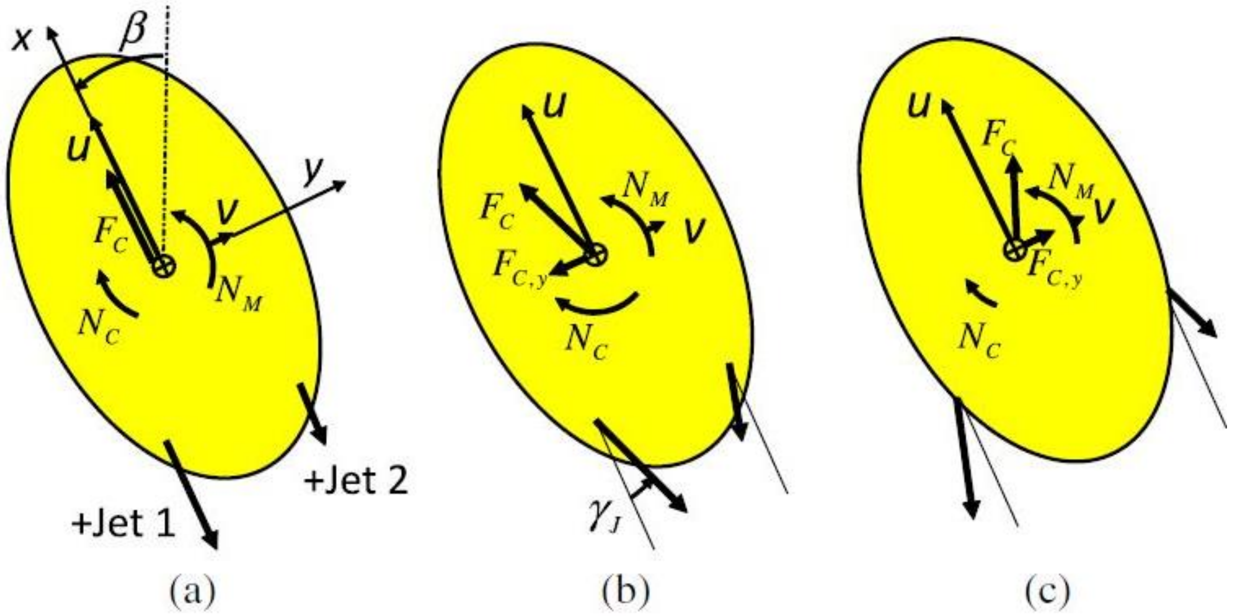
* A. Mazumdar, H. H. Asada, "Control-Configured Design of Spheroidal, Appendage-Free, Underwater Vehicles," IEEE Trans. Robotics, Vol. 30, No. 2, April 2014

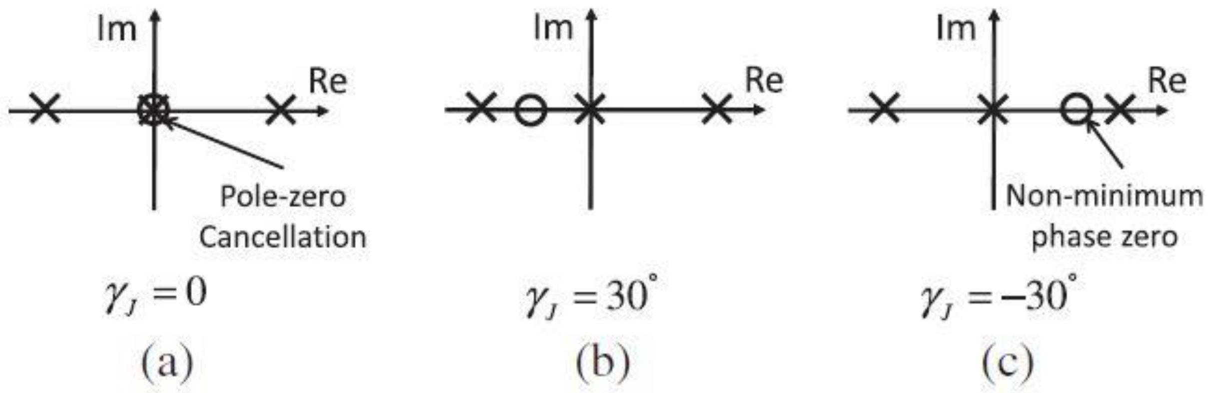
Control-Configured Underwater Vehicle*

- Transfer function of linearized dynamics

$$\frac{\Delta\psi(s)}{\Delta V(s)} = \frac{(sG_M m_y + \Delta m_a U_c G_F \sin\gamma_J)}{s\,(m_y I_z s^2 - U_c^2 m \Delta m_a)}$$

- Parallel jets: Pole-zero cancellation
  - No control on side-slip
  - Loss of controllability
- Inward jets:
  - Both side-slip and Munk moment opposed
  - Zero in LHP
- Outward jets:
  - Cancelling one tends to amplify the other
  - NMP zero
- Note: Unstable in all cases





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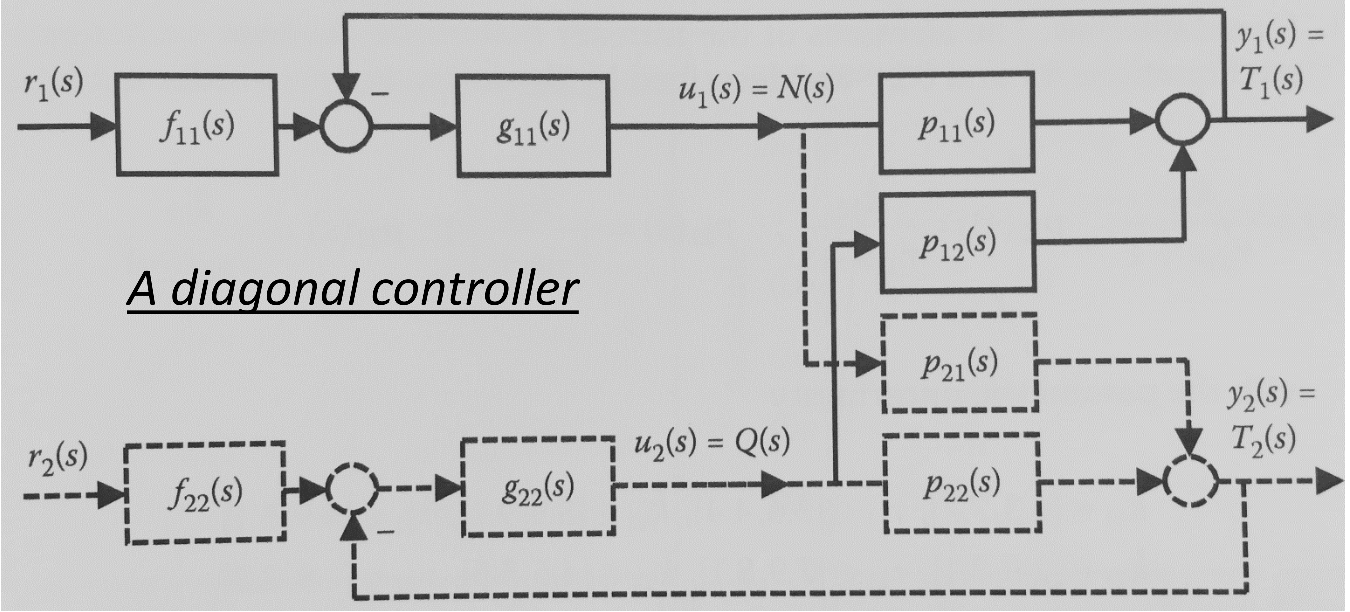
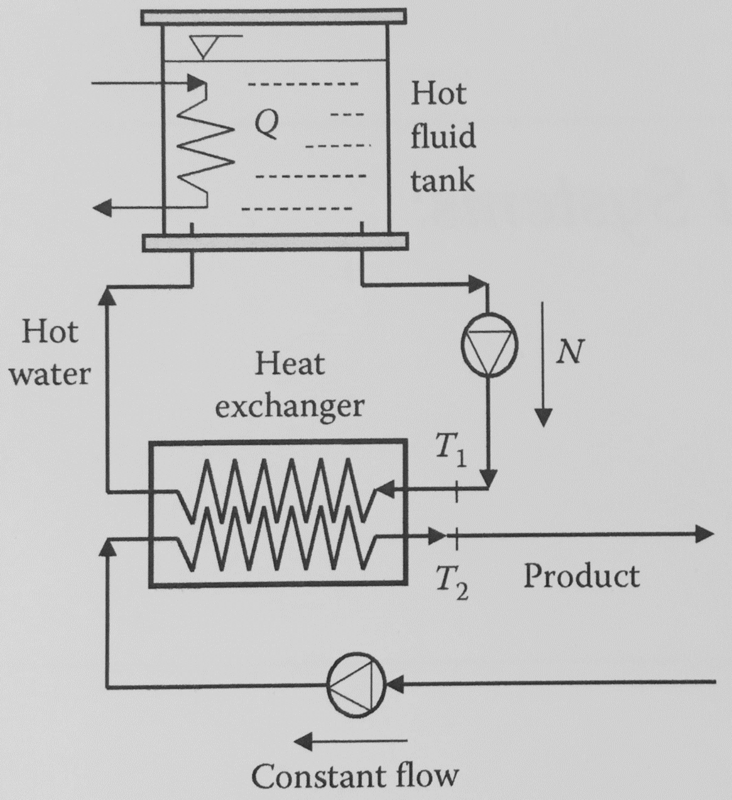
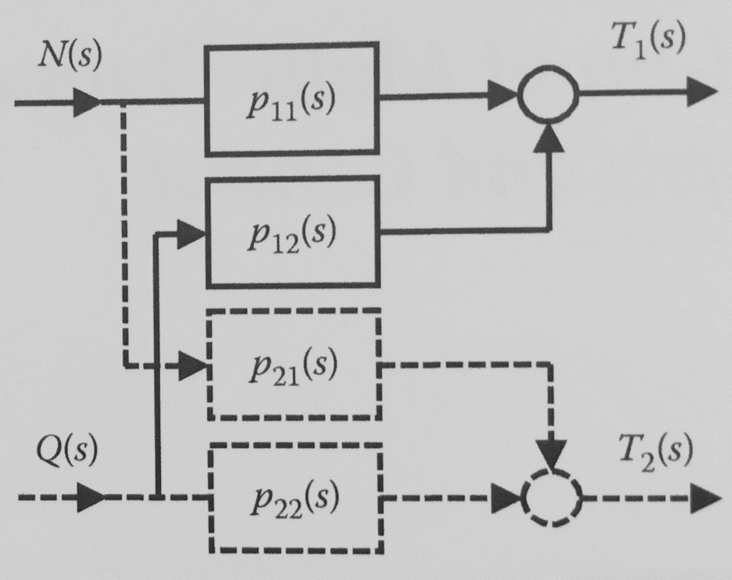
MIMO systems: Heat exchanger control*

- MIMO systems are dynamically coupled
  - Transfer function is a matrix instead of scalar
  - Typical control methods involve pairing of specific input variables to specific output variables
  - The pairing can be based on Relative Gain Array (RGA) analysis and/or analysis of the dynamic equations
  - However, the inherent coupling that will still exist



A diagonal controller





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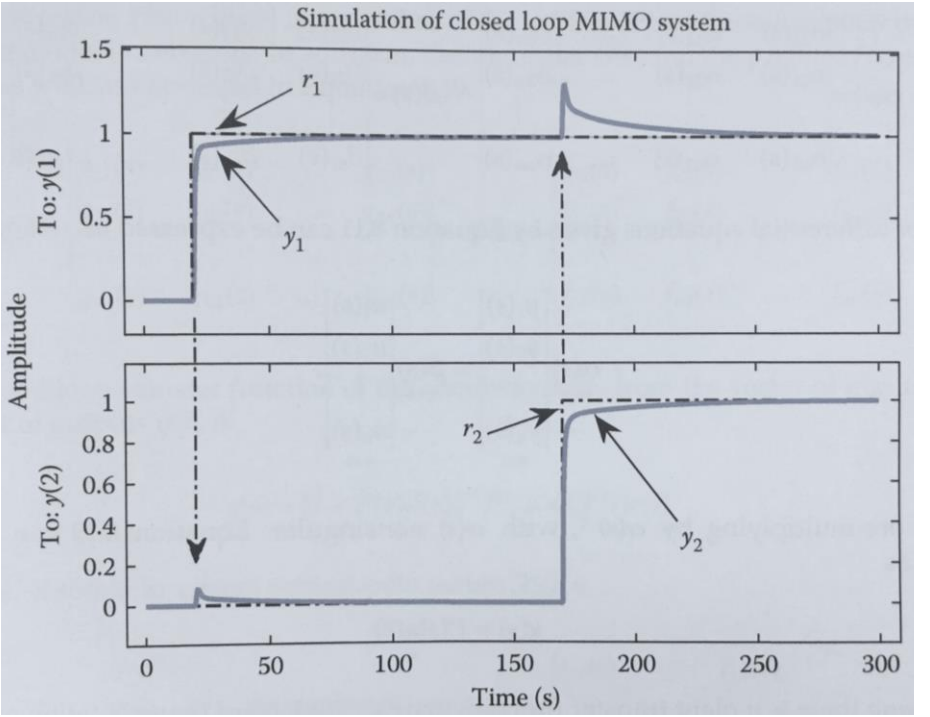
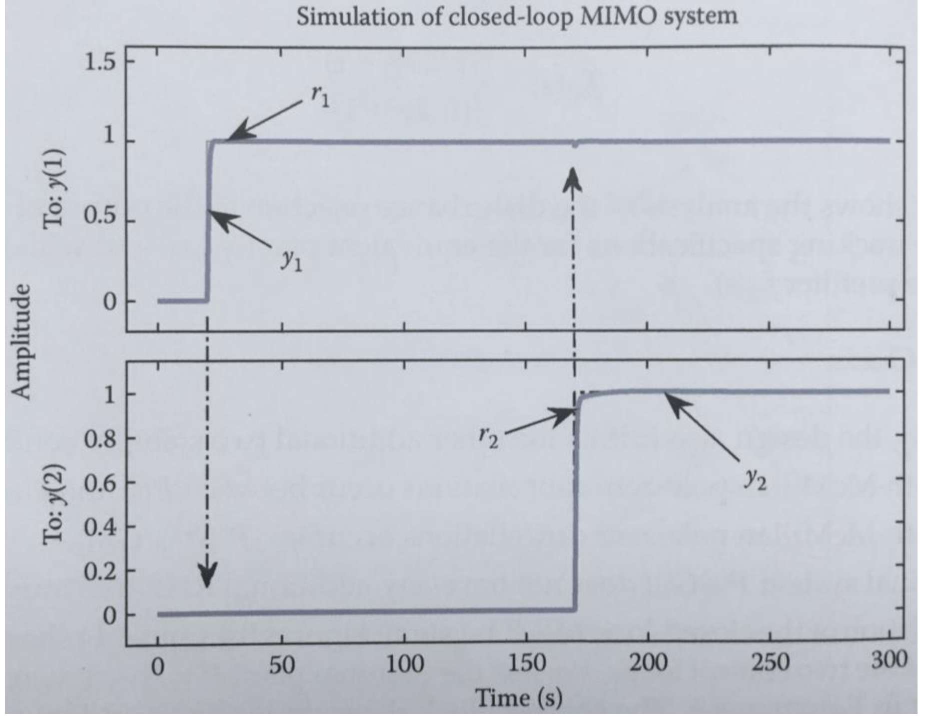
MIMO: Heat exchanger control*

- Internal coupling persists in pairing based control
  - Set point changes in references cause perturbation in the coupled variables
  - Desire a performance to achieve the result shown below – a significantly better decoupling of dynamics
- Approaches to achieve this:
  - Through control design
    - E.g. feedback based decoupling, redefining control inputs
  - Through control co-design
    - Revisiting and modifying system design
    - E.g. introducing alternate flow paths (actuations)
    - Also exploring if there is any fundamental obstacle to decoupling





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